MAC-MOA 19.1.2

Sensitivity Analysis of Groundwater Flow and Transport Models for the Moab Project Site

Letter Report

June 2002

Prepared by
U.S. Department of Energy
Grand Junction Office
Grand Junction, Colorado

Work Performed Under DOE Contract Number DEBAC13B96GJ87335
Task Order Number MAC02–16

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Introduction

The U.S. Department of Energy (DOE) Grand Junction Office is developing an update to their Plan for Remediation for the Moab Project Site. The groundwater compliance strategy presented in the draft Plan for Remediation was formulated on the basis of modeling predictions prepared by the former trustee and its consultant Shepherd-Miller, Inc. (SMI). This report presents a review of the model and results of a sensitivity analysis performed by MACTEC–ERS (MACTEC) to better understand uncertainties in the groundwater compliance strategy presented in the draft Plan for Remediation. Results of the model review and sensitivity analysis will be used to update the site conceptual model and to lay the foundation for an updated flow and transport model.

During MACTEC's review of the SMI model (SMI 2001), it was discovered that Southwest Research Institute, a U.S. Nuclear Regulatory Commission (NRC) contractor, had completed an earlier modeling effort. MACTEC also evaluated that model, hereafter referred to as the NRC model.

The model evaluation was designed to address the following questions:

- What are the sensitive parameters for the current models?
- Are the site conceptual models and numerical models supported by site-characterization data?
- Do the current models adequately assess the effectiveness of the proposed remedial alternatives?
- Do the current models provide plausible estimates of time to achieve compliance?

Figure 1 shows a flow chart of the model evaluation process. SMI and NRC each used a transient model to evaluate three alternatives: no action, cap-in-place and source removal. This review describes and compares both the transient and steady-state models that were used by SMI and NRC. After the site conceptual model and numerical models are updated, DOE will compare the effectiveness of the cap-in-place and the relocate alternatives.

Steady-State Models

The steady-state models indicate how SMI and NRC conceptualized the site. The conceptual models are strikingly different. Figures 2 and 3 summarize the parameter values used in the SMI and NRC models, respectively. Figures 4, 5, and 6 present in plan view the distribution of boundary conditions and hydraulic parameters for both models.

Both SMI and NRC created models consisting of three layers. The NRC model is horizontally discretized (divided) into 90 rows and 70 columns having uniform widths of 100 feet (ft). Vertically, the NRC model consists of three layers having thicknesses of less than 20 ft, 30 ft, and 30 ft, from top to bottom, respectively. Hydraulic conductivity in the NRC model is uniform in the horizontal and vertical directions. In layers 1, 2, and 3, the horizontal hydraulic conductivities are 22 ft/day, 22 ft/day, and 2.2 ft/day, respectively. The origin for the NRC model is x = 2185491.0, y = 6659578.9, and rotation is 35 degrees.

The SMI model was discretized into 100-ft by 100-ft nodes using 78 rows and 75 columns. The thickness of the model layers varies. The total thickness of the model varies from approximately 10 to 140 ft. Horizontal hydraulic conductivity of the SMI model varies from 35 to 175 ft/day. The origin for the SMI model is $x = 2185907.3$, $y = 6659565.1$, and rotation is 42 degrees. The SMI model contains inactive cells in Layer 3 beneath the tailings pile. The purpose of these cells is to simulate assumed no-flow conditions in the Paradox Group that arguably underlie a portion of the site. The existence of, and depth to, this bedrock group below the site has not been confirmed with drill-hole data.

The SMI model was calibrated to water levels measured at 11 locations. The NRC model was calibrated to match the general pattern of head distribution rather than the head at a specific point. According to NRC, the calibrated model "matched measured interpolated water levels within ± 1.5 ft" (NRC 1998, p.4-1). To compare how well both models fit the same set of observed heads, head targets used by SMI were imported into the NRC model. Table 1 compares how both models matched the target heads. The ratio of standard deviation to range (in head) conveys a sense of how well both models match observed water levels. If the ratio of the root-mean-squared (RMS) error to the total head loss in the system is small, the errors are only a small part of the overall model response (Anderson and Woessner 1992). James Rumbaugh (Environmental Simulations, Inc., personal communication, July 13, 1998) uses as a goal to reduce the standard deviation/range-in-head to below 10 percent, and if practical, below 5 percent. SMI's ratio of 16 percent, versus NRC's ratio of 6.2 percent, indicates that the NRC model matches the observed water levels better than the SMI model.

NRC's model, however, has considerable bias, as evidenced by the negative residuals. SMI's model has the opposite bias because the residuals are positive. In an ideal model, the residuals should be evenly distributed about zero (Anderson and Woessner 1992). For example, the number of predicted heads that exceed measured heads should roughly equal the number of predicted heads that do not exceed.

Table 2 shows the sources and sinks for the water in both flow models. The SMI model assumes that bedrock units contribute approximately 80 percent of the water in the system. The NRC model assumes no bedrock recharge and that areal recharge and constant-head (Moab Wash) account for 60 percent and 40 percent of the water in the system, respectively. The SMI model, however, is transmitting approximately 10 times more water than the NRC model.

Approximately 75 percent of the outflow from the SMI model occurs as discharge to the Colorado River. The SMI model uses river cells, which function as head-dependent flux, to simulate the Colorado River. Conductance values and head values for the riverbed material are necessary to fully define river cells. SMI did not document whether actual field data support the choice of parameters used for the river cells. In contrast, the NRC model uses constant-head cells to simulate the river.

The remaining 25 percent of outflow from the SMI model is evapotranspiration (ET) from the salt cedar plant community. The SMI model simulates ET with the MODFLOW recharge package and represents the ET with a constant negative-recharge flux. The flux rate used in the model was obtained from a study of a salt cedar community in southeastern New Mexico (Weeks 1987). Use of the MODFLOW recharge package rather than the ET package implies that the salt cedar community constantly removes water from the aquifer, regardless of the depth to water and depth of root penetration. The ET package removes groundwater from the model as a function of the depth to water and root penetration.

From Table 2 it is clear that the bedrock formations are an important source of water in the SMI model. However, only a few drill holes at the site ever contacted bedrock (probably Moenkopi), and they were not instrumented to measure hydraulic head in the bedrock. Consequently, the assumed contribution of fresh water from Glen Canyon Group bedrock aquifers is not supported by data. Two water supply wells that tap the Glen Canyon Group do exist near the entrance to Arches National Park and obtain high quality water from along the Moab Fault Zone. One of them produces 12 gallons per minute (gpm) from a depth of 123 ft, and the other produces 30 gpm from a depth of 172 ft (Blanchard 1990). Static water level in both wells is approximately 100 ft below ground surface, indicating minimal artesian pressure.

In addition, recent salinity measurements made by MACTEC suggest that salinity increases with depth at the site. For upwelling to be an important source of freshwater at the site, the deeper groundwater would require a freshwater signature. Also, artesian pressures would increase with depth. Recent data collected at the site do not support either of these conditions.

SMI confirmed earlier work by others that brine exists beneath a lens of freshwater at the site. To explicitly account for the physical hydrologic system, the groundwater model should include the ability to simulate variable density. SMI represented the top of the brine with a no-flux boundary condition and used MODBRINE, an external FORTRAN program, to adjust the MODFLOW layer in accordance with the Ghyben-Herzberg relation to account for brine encroachment into the freshwater/brine transition zone. NRC did not account for the movement of the brine at all.

The NRC model assumes that constant-head exists at the mouth of Moab Wash. Although there may be some contribution to ground water from Moab Wash during runoff events, and possibly a baseflow component, there does not appear to be a constant head. The term “constant head” implies that a truly limitless source of water exists at that location. The Colorado River, for example, is considered a constant head. Because Moab Wash only flows ephemerally, it cannot be considered a limitless source of water. The use of a constant head boundary at this location, coupled with a constant head boundary along the Colorado River, results in overprescribed boundaries in this model. It will be shown later that the NRC model is practically insensitive to the choice of flow parameters because the boundaries are overprescribed.

Figure 7 presents the steady-state water level contours for both models. As shown in Figure 7, a large portion of the SMI model contains dry cells in Layer 1. The dry cells probably form because the model cells in Layer 1 are excessively thin and do not intersect the groundwater. Elimination of dry cells in the SMI model would improve overall reliability of the model. The NRC model has no dry cells.

Sensitivity Analysis

According to Anderson and Woessner (1992), "The purpose of sensitivity analysis is to quantify the uncertainty in the calibrated model caused by uncertainty in the estimates of aquifer parameters, stresses, and boundary conditions. During a sensitivity analysis the calibrated values for hydraulic conductivity, storage parameters, recharge, and boundary conditions are systematically changed within the previously established plausible range."

Sensitivity analyses are conducted to identify model parameters and boundary conditions that influence model results. Figures 2 and 5 show that hydraulic conductivity in the SMI model covers a range of 139 individual zones and that the highest hydraulic conductivities occur downgradient of the tailings pile. Many of these hydraulic conductivity zones have such limited areal extent that varying them has little effect on the simulated water levels. This is illustrated in Figure 8 by selecting the five zones with the largest areal extent and evaluating their sensitivity. K zones 35, 49, 50, 60, and 99 (ft/day) each have the five largest areal extents and practically no sensitivity over model outcome. Therefore, zones with smaller areal extent would be even less sensitive.

Layers 1 and 2 of the NRC model are each composed of hydraulic conductivity values of K = 22 ft/d, while layer 3 is set to 2.2 ft/d. As shown in Figure 8, there is practically no effect on simulated water levels if the hydraulic conductivity of just one layer is varied. However, if the hydraulic conductivity of Layers 1 and 2 is reduced by more than 50 percent, the residual error increases markedly. The absence of a conductive layer is what forces the water table higher when Layers 1 and 2 conductivities are lowered.

Model sensitivity to recharge and boundary conditions was also evaluated. Figure 9 presents the results of these evaluations for the SMI and NRC models. These analyses show that the SMI model is somewhat sensitive to 10-fold reductions in riverbed conductance in Layer 1 and general-head boundary conductance in Layer 3. In addition, the model is affected by intensifying the negative-recharge parameter that describes the salt cedar community. Figure 9 shows that the NRC model is sensitive to recharge if it increases twofold over the baseline condition.

Table 1. Comparison Summary of Head Calibration for SMI and NRC Models.

Location	Error in SMI Model	Error in NRC Model
AMM-3	1.702225	–1.201362
MW-2-R	–0.200000	–0.781634
TP-03	0.093928	–0.559923
AMM-2	1.159346	–0.960588
ATP-2-S	1.832740	–0.926606
ATP-3	–0.548388	–0.495153
TP-01	0.160512	Located in no-flow region
TP-02	0.074529	–0.630841
TP-08	1.535670	–1.034620
TP-09	1.430725	–0.914757
AMM-1	0.257954	–0.034251
Res. std. dev	0.816904	0.318721
Sum of squares	12.453255	6.700590
Range	5.100000	5.100000
Std/range	0.160177	0.062494

Table 2. Water Balance Summary for SMI and NRC Models

Model	Flow Component	Inflow (ft^3/day)	Outflow (ft^3/day)	Percent Error
SMI	Lateral inflow from bedrock	22,802		
	Vertical upwelling from bedrock	62,744		
	Colorado River[a]	15,469	76,941	
	Recharge	3866		
	“Negative” recharge[b]		24,800	
	Total	104,881	101,741	3.0
NRC	Constant head	4796	10,729	
	Recharge	5976		
	Total	10,772	10,729	0.4

[a]Includes minor contribution from Courthouse Wash
[b]Consists of evapotranspiration in salt cedar plant community

UCODE Simulations

Model evaluation was performed using UCODE (Poeter and Hill 1998), a universal inverse modeling program developed as a collaborative project between the U.S. Geological Survey and the International Groundwater Modeling Center at the Colorado School of Mines, in cooperation with the U.S. Army Corps of Engineers Waterways Experiment Station. Inverse modeling, or parameter estimation modeling, is an automated calibration technique that works by finding parameter values (e.g., hydraulic conductivities, recharge) that minimize the sum of the squares errors, also called the objective function or objective function value, for a given model configuration.

For this application, the goal was not to obtain optimal calibrated parameter values; rather, it was assumed that the parameter values in the models were optimal. UCODE was only used to determine the sensitivities, parameter calibration statistics (standard deviation and 95 percent confidence intervals), and correlations, if any, of the calibrated parameters used in the two models.

With UCODE, it is possible to evaluate the head component of head-dependent boundaries rather than simply the conductance component. Therefore, the UCODE simulations are especially diagnostic when head-dependent boundaries are being investigated.

SMI Model

Table 3 summarizes the UCODE results for the SMI model. The results show that regardless of target type most parameters are relatively insensitive. The exceptions are heads associated with the general-head and river boundaries. Insensitive parameters are difficult to calibrate because changes in parameter values produce minimal changes in the predicted target values. However, parameter sensitivity can sometimes be improved with use of different or additional targets.

Due to the relatively large number of parameters to be evaluated and the shortage of targets, not all the parameters could be evaluated simultaneously for the head-target, and head-target and flux-target evaluations. There were sufficient targets to evaluate all parameters simultaneously when using head, flux, and prior information. To calculate 95 percent confidence intervals, standard deviations, and correlations, the number of targets must exceed the number of parameters to be estimated by at least one (Poeter and Hill 1998). To overcome this limitation, the UCODE evaluation was performed by dividing the parameters into three groups: (1) hydraulic conductivities and recharge, (2) hydraulic conductivities and general-head conductances and heads, and (3) hydraulic conductivity and river conductances and heads. The statistics generated by UCODE are a function of the number of parameters estimated. Thus, the reported statistics are not completely representative of the statistics for the entire parameter ensemble. However, comparison of the magnitude of the calculated hydraulic conductivity 95 percent confidence limits for the three evaluation groups shows that values change minimally, suggesting that the reported values do provide some indication as to how representative the targets are.

In general, regardless of target types used in the evaluation, the predicted 95 percent confidence intervals for the parameters are large, indicating the targets used to calibrate the model do not contain enough information to uniquely calibrate the flow model. The confidence intervals for the five hydraulic conductivity parameters are greatly reduced with the introduction of prior information about those parameters. However, prior information should be used judiciously, because the prior information may not be entirely representative.

In general, parameters cannot be estimated independently if their correlation factors exceed 0.95 (Poeter and Hill 1998). Significant parameter correlation occurs in the SMI model when head targets and head-and-flux targets are used to calibrate the model. In these cases, parameters cannot be estimated independently; rather, one of the correlated parameters must be fixed before model calibration can proceed.

In summary, the targets used to calibrate the SMI groundwater flow model do not hold enough information to uniquely calibrate the flow model, as shown by the relatively low parameter sensitivities, large ranges in the 95 percent confidence interval, and significant correlation between parameters.

NRC Model

Table 4 summarizes the NRC model UCODE results. Each of the parameters is relatively insensitive, regardless of target type. Insensitive parameters are difficult to calibrate because changes in parameter values produce minimal changes in the predicted target values.

The large range between the upper and lower 95 percent confidence intervals for the head-target and head-and-flux target scenarios indicate that the parameters are insensitive. The confidence intervals represent the likely precision of the parameter estimates for a given set of targets. Different target types, locations, and numbers will result in different 95 percent confidence intervals. Thus, 95 percent confidence intervals quantify how well the target values represent the model as configured and not the accuracy of the simulated conceptual model. The simulated conceptual model may or may not be representative; the targets simply do not contain enough information to prove or disprove the configuration.

Table 3 : Summary of Parameter Estimation Results for the SMI Model

Scenario	Head Targets				
Parameter	**Lower 95 percent CI**	**Calibrated Value**	**Upper 95 percent CI**	**Standard Deviation**	**Composite Sensitivity**
K1	-4.53e4	35	4.54e4	1.05e4	0.02
K2	-8.34e3	50	8.44e3	1.95e3	0.24
K3	-8.15e3	75	8.30e3	1.91e3	0.13
K4	-1.12e4	100	1.14e4	2.63e3	0.32
K5	-1.63e4	175	1.66e4	3.82e3	0.06
Recharge 1	-8.81e-1	2.28e-4	8.81e-1	2.05e-1	0.03
Recharge 2	-5.05e-1	4.46e-4	5.06e-1	1.17e-1	0.05
Recharge 3	-1.34	-8.00e-3	1.33	3.10e-1	0.28
RIV 1 Con	-5.42e4	2500	5.92e4	1.78e4	0.14
RIV 2 Con	-2.95e5	2500	3.00e5	9.36e4	0.03
RIV 1 Head	-	variable	-	4.08e-8	1.02e12
RIV 2 Head	-2.64e3	3951.91	1.05e4	5.19e2	345
GHB 1 Con	-6.12e4	50	6.13e4	4.82e3	0.07
GHB 2 Con	-2.63e4	50	2.64e4	2.08e3	0.55
GHB 1 Head	-1.48e4	3958	2.27e4	1.47e3	111.00
GHB 2 Head	3.91e3	3958	4.01e3	3.87	15110.0
Head and Flux Targets					
K1	-7.32e3	35	7.39e3	2.63e3	0.15
K2	-9.34e2	50	1.03e3	3.54e2	1.22
K3	-1.90e3	75	2.05e3	7.10e2	0.73
K4	-9.50e2	100	1.15e3	3.78e2	3.63
K5	-7.90e3	175	8.25e3	2.91e3	0.05
Recharge 1	-2.98e-2	2.28e-4	3.03e-2	1.08e-2	0.26
Recharge 2	-5.00e-2	4.46e-4	5.09e-2	1.82e-2	0.16
Recharge 3	-1.17e-1	-8.00e-3	1.01e-1	3.94e-2	2.98
RIV 1 Con	-3.77e4	2500	4.27e4	1.56e4	0.43
RIV 2 Con	-3.12e4	2500	3.62e4	1.31e4	0.25
RIV 1 Head	-	variable	-	4.43e-12	9.33e11
RIV 2 Head	3.81e3	3951.91	4.09e3	1.13e-2	2471
GHB 1 Con	-4.01e3	50	4.11e3	1.28e3	0.38
GHB 2 Con	-2.12e2	50	3.12e2	8.23e1	4.41
GHB 1 Head	3.74e3	3958	4.18e3	6.91e1	518.00
GHB 2 Head	3.96e3	3958	3.96e3	5.69e-1	14220.0
Head, Flux, and Prior Information Targets					
K1	3.3	35	66.7	13.8	0.15
K2	4.7	50	95.3	19.6	1.22
K3	7.1	75	143.0	29.5	0.73
K4	9.4	100	191.0	39.3	3.63
K5	16.4	175	334.0	68.8	0.05
Recharge 1	-1.76e-3	2.28e-4	2.21e-3	8.61e-4	0.26
Recharge 2	4.73e-5	4.46e-4	8.45e-4	1.73e-4	0.16
Recharge 3	-1.04e-1	-8.00e-3	8.84e-2	4.18e-2	2.98
RIV 1 Con	2.35e2	2500	4.76e3	9.82e2	0.43
RIV 2 Con	2.35e2	2500	4.77e3	9.82e2	0.25
RIV 1 Head	-	variable	-	1.08e-8	9.33e11
RIV 2 Head	3.89e3	3951.91	4.02e3	2.74e1	2.47e3
GHB 1 Con	4.70	50	95.3	1.96e1	0.38
GHB 2 Con	4.70	50	95.3	1.96e1	4.41
GHB 1 Head	3.82e3	3958	4.09e3	5.92e1	518.00
GHB 2 Head	3.94e3	3958	3.97e3	5.93	14220.0

Parameter Correlation

Head Targets	Head and Flux Targets	Head, Flux and Prior Information Targets
Kx1 – Kx2 : 0.96 Kx1 – R3 : -0.97 R1 – R2 : -0.97 Kx4 – GHB1 head : 0.98 RIV2 conductance – RIV2 head : -0.96	RIV2 conductance – RIV2 head : -0.96 GHB1 conductance – GHB1 head : -0.99	None greater than absolute 0.95.

Table 4 : Summary of Parameter Estimation Results for the NRC Model

Scenario	Head Targets				
Parameter	**Lower 95 percent CI**	**Calibrated Value**	**Upper 95 percent CI**	**Standard Deviation**	**Composite Sensitivity**
K1	-7.37e2	22	7.81e2	3.10e2	1.19
K2	-8.93e3	22	8.98e3	3.66e3	0.10
K3	-5.61e3	2.2	5.62e3	2.29e3	0.01
Recharge 1	-6.76e-3	2.00e-4	7.16e-3	2.84e-3	1.27
Head and Flux Targets					
K1	-1.24e3	22	1.29e3	5.35e2	1.67
K2	-2.09e4	22	2.10e4	8.86e3	0.13
K3	-1.28e4	2.2	1.29e4	5.43e3	0.01
Recharge 1	-3.79e-3	2.00e-4	4.19e-3	1.69e-3	2.98
Head, Flux, and Information Targets					
K1	15.3	22	28.7	2.99	1.67
K2	15.1	22	28.9	3.08	0.13
K3	1.51	2.2	2.89	0.31	0.01
Recharge 1	7.28e-5	2.00e-4	3.27e-4	5.71e-5	2.98

Parameter Correlation

Head Targets	Head and Flux Targets	Head, Flux and Prior Information Targets
None greater than absolute 0.95.	Kx1 and Kx2 : -1.00 Kx2 and Kx3 : -0.95 Kx3 and R1 : 1.00	None greater than absolute 0.95.

In general, parameters having correlation factors greater than 0.95 or less than –0.95 cannot be estimated independently (Poeter and Hill 1998). For the NRC model, significant parameter correlation exists when both heads and flux targets are used simultaneously. As shown in Table 4, hydraulic conductivities of zones 1 and 2 are perfectly inversely correlated. Similarly, hydraulic conductivities of zones 2 and 3 are almost perfectly inversely correlated. Finally, hydraulic conductivity of zone three and recharge are perfectly correlated. Correlated parameters cannot be estimated independently; rather, one of the correlated parameters must be fixed before model calibration can proceed.

In summary, the targets used to calibrate the NRC groundwater flow model do not hold enough information to uniquely calibrate the flow model, as shown by the relatively low parameter sensitivities, large 95 percent confidence interval range, and significant correlations (for head and flux targets) between parameters.

Transient Simulations

Predictive simulations for DOE’s remediation plan are based on three alternatives: no action, cap in place, and source removal.

As a rule, initial conditions, or initial heads, must be specified in order to run a transient model. SMI and NRC each used outputs from their steady-state models to set initial heads for their respective transient models. In addition, the SMI transient model used K_d values obtained from literature for the ammonium and uranium of 0.00637, and 0.00159 (assumed units of ft^3/lb_{mass}), respectively. These K_d values were also assigned to the NRC Model to conduct this study.

No Action Alternative

Table 5 shows the processes that were considered in the no action alternative. The no action alternative assumes that the tailings pile is left in place in its present condition. The assumed long-term infiltration rate through the pile is 1×10^{-7} centimeters per second (cm/s) (3.9 gpm). This infiltration rate represents 14 percent of average annual precipitation. Transient drainage of water stored in the tailings pile occurs during the first 25 years of the simulation; it conveys 21.6 million cubic feet of water to the alluvial ground water system during the 25-year period. The transient-flow contribution is derived from modeling done by SRK Consulting (2000). Because vertical band drains were installed in the tailings pile during the past 2 years, and the volume of water recovered from those drains has not been monitored continuously, the transient flow component is considered a sensitive model parameter. Figure 10 shows time-concentration plots of the predicted ammonia and uranium concentrations using both the SMI and NRC models for the no action alternative. These results show that the no action alternative will not meet the 0.044 mg/L ground water standard for uranium within 100 years. The SMI model indicates that concentrations would decrease markedly and that uranium levels would begin dropping below the standard after approximately 200 years. The NRC model shows that little to no reduction in concentrations would occur through the entire simulation. The difference in the two models is that the observation wells in the SMI model are located in the salt cedar zone, where negative recharge removes contaminated ground water at a constant rate and eventually restores the aquifer. Particle tracking simulations show that the particles originating at the tailings pile would be captured in the salt cedar zone.

Cap-in-Place Alternative

Table 5 summarizes the cap-in-place alternative. The conceptualization of this scenario is similar to the no action alternative except infiltration through the tailings pile is restricted to a rate of 1×10^{-8} cm/s (0.39 gpm) with a cover constructed of engineered fill. Transient drainage from the tailings pile is assumed to occur for 25 years, as in the no action alternative. Figure 11 presents the results for SMI's and NRC's cap-in-place simulations. Both models predict that this alternative would fail to achieve compliance with standards within 100 years. However, SMI's cap-in-place model shows that concentrations would decline faster than with the no action alternative. NRC's cap-in-place model shows that concentrations would be one order of magnitude lower than with the no action alternative.

Source Removal Alternative

Table 5 summarizes the source removal alternative. The concept of this alternative is that the tailings are removed and no longer provide a source of contaminated pore water. The area of the model formerly occupied with tailings has a recharge that matches the areal recharge value of approximately1×10^{-7} cm/s. The K_d values for the ammonium and uranium are practically zero, as mentioned above. However, using K_d values that are practically zero, the most favorable of scenarios for groundwater cleanup, natural flushing still fails to reduce the uranium concentrations in the floodplain aquifer even after 100 years. Figure 12 presents the results for the SMI and NRC source removal models.

Table 5. Summary of Processes Considered During This Evaluation

Remedial Action Alternative	Processes Considered
No action	• Initial conditions from steady-state model • Transient drainage considered • 1×10^{-7} cm/s infiltration rate through cell • Pore water chemistry of cell • Initial concentrations of NH_4, U, and SO_4 • 500-year projection
Cap in place (with natural flushing)	• Initial conditions from steady-state model • Transient drainage considered • 1×10^{-8} cm/s infiltration rate through cell • Pore-water chemistry of cell • Initial concentrations of NH_4, U, and SO_4 • 500-year projection
Source removal	• Initial conditions from steady-state model • Transient drainage considered • 1×10^{-7} cm/s infiltration rate through cell • Pore water concentration = 0 at tailings site • 500-year projection
Cap in place (with active treatment)	Not evaluated

Conclusions

- UCODE modeling shows that both models contain boundary conditions that may be correct; however, the conditions are not supported with existing data. Therefore, neither model can adequately assess the effectiveness of the proposed remedial action.

- Single-parameter sensitivity analysis and UCODE modeling show that both models are insensitive to the choice of boundary conditions and parameter values—K, recharge, general-head, and river-cell conductances and heads.

- Both models are based on site conceptual models that may be correct; however, they are not consistent with data sets. An alternate conceptual model should be developed that matches the existing data sets more closely.

- The SMI and NRC models are at opposite ends of the spectrum with respect to the water budget: the SMI model is on the high end, and the NRC model is on the low end. Neither model shows that natural flushing will be effective as a stand-alone strategy at removing uranium concentrations to levels below the 0.044 mg/L standard in 100 years. Because the two existing models probably bracket the actual water budget for the site, it is probably safe to conclude that natural flushing will be an ineffective strategy if relied upon exclusively.

SMI Model

- The SMI model assumes that lateral inflow and upwelling from the Glen Canyon Group contributes 80 percent of the freshwater in the flow system; however, there are no site characterization data that support the assumption. Moreover, previous borehole logs at the site identified bedrock as Moenkopi Formation.

- UCODE modeling results show that SMI's choice of head and conductance values in the general-head boundaries and river-cell arrays may be correct; however, they are not supported with data collected at the site.

- The SMI model uses negative recharge to remove groundwater from the flow system. The negative recharge flux value is obtained from a study performed in southeastern New Mexico and is unconfirmed with site data. In the model, negative recharge is 100-percent efficient; therefore, it does not account for the depth to groundwater, evapotranspiration-extinction depth, and seasonal fluctuations.

- Transient drainage from the tailings is assumed to occur over 25 years and contribute 21.6×10^6 ft^3 of pore water to the flow system. This estimate is based on modeling performed by SRK Consulting (2000). The value does not account for consolidation water already drained from the tailings pile and is thus conservative.

- The SMI model uses a spatially variable hydraulic conductivity field that honors the point hydraulic conductivity measurements at three locations, and contains interpolated values elsewhere.

- SMI represented the top of the brine with a no-flux boundary condition and used MODBRINE, an external FORTRAN program, to adjust the layer thickness in MODFLOW to account for brine encroachment into the freshwater/brine transition zone.

- For a model of floodplain alluvium, the SMI model contains an excessive number of dry cells. These cells do not add value to either the steady-state model or the transient model that uses the steady-state heads for initial conditions.

NRC Model

- The NRC model assumes that constant head exists at the mouth of Moab Wash. Although there may be some contribution of water from Moab Wash due to underflow and ephemeral flow, the use of constant head is not supported with site data.

- Head calibration for the NRC model meets minimum acceptance criteria recommended by leaders in the modeling profession; however, there is considerable bias in all the calibration targets.

- Because constant head cells are established on both the upgradient and downgradient faces of the flow model, the NRC model is overprescribed with head boundaries. Single parameter sensitivity analysis and UCODE modeling show the model is not particularly sensitive to either hydraulic conductivity or recharge.

- The NRC model did not account for variable density effects of the brine.

- Transient drainage from the tailings is assumed to occur over 25 years and contribute 21.6×10^6 ft^3 of pore water to the flow system. This estimate is based on modeling performed by SRK Consulting (2001). The value does not account for consolidation water already drained from the tailings pile and is thus conservative.

Recommendations

(1) Develop a revised site conceptual model. The revised site conceptual model would be developed from appropriate field data described in (2) below. Components of the revised site conceptual model would consist of defining the following:

- Boundary conditions at the mouth of Moab Wash.
- Flux component along the contact regions between the alluvium and bedrock.
- Flux component from underlying bedrock (Paradox Formation and Glen Canyon Group).
- Boundary conditions at the mouth of Courthouse Wash.
- Contribution of water and chemical mass from the tailings pile.
- Magnitude of evapotranspiration flux.
- Chemical source conditions near the uranium "hot spot" near the former millsite.
- Water budget values for each flow component.
- Location of and equivalent freshwater head values for brine and brackish ground waters.
- 3-dimensional schematic drawing of the site showing all boundaries and fluxes.

(2) Obtain the following characterization data:

- Identify subcropping bedrock formations and measure top of bedrock elevations.
- Nested monitoring wells to monitor bedrock/alluvium interaction.
- Collect piezometer data in the tailings pile.
- Density of equivalent freshwater head values for brine and brackish ground waters.
- Measure the volume of all liquids released during consolidation of the tailings pile.
- Characterize evapotranspiration along salt cedar zones.

(3) Ensure the numerical model contains verifiable targets, boundary conditions, and flow parameter values.

(4) Establish head targets and flux targets; define calibration-acceptance criteria for future numerical modeling.

(5) Identify a numerical code that accounts for variable density explicitly and begin 2-dimensional cross-section simulations of flow and transport.

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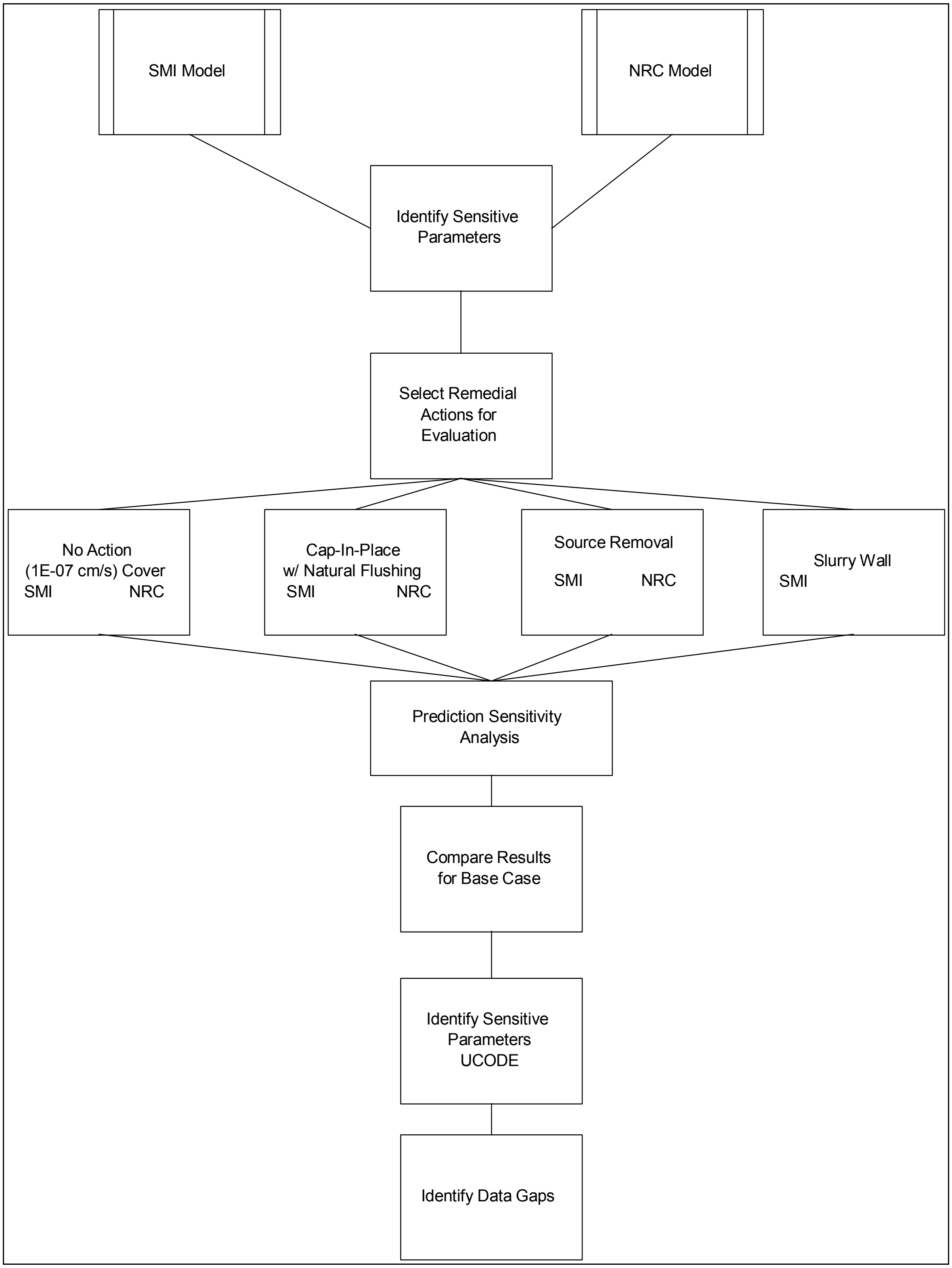


Figure 1. Model Review Process

SMI's steady state model

Steady-State Model
Aquifer Properties

Parameter	Dimensions	Layer 1	Layer 2	Layer 3	
Aquifer Flow Hydraulic Parameters					
Horizontal hydraulic conductivity (K_h)	feet per day	Ranges 35–50	Ranges 49–174	Ranges 60–174	
Vertical hydraulic conductivity (K_v)	feet per day	Ranges 4.2–6.0	Ranges 5.9–20.9	Ranges 7.2–20.9	
Specific yield (S_y)	dimensionless	0.25	Ranges 0.1–0.28	Ranges 0.1–0.276	
Storage coefficient (S)	dimensionless	0.0077	Ranges 0.0002–0.0092	Ranges 0.0002–0.009	
Porosity	dimensionless	0.35	0.35	0.35	
Aquifer Transport Parameters					
K_d	cubic feet per pound	0	0	0	
Aquifer bulk density		157	157	157	
Dispersivity	feet	0	0	0	

Recharge Amounts

Area/Feature	Recharge Rate (ft/day)
Areal recharge	0.000228
Disposal cell	0.000446
Evapotranspiration areas	–0.008

Figure 2. Summary of Parameters for SMI Steady-State Model

Steady-State Model
Aquifer Properties

Parameter	Dimensions	Layer 1	Layer 2	Layer 3
Aquifer Flow Hydraulic Parameters				
Horizontal hydraulic conductivity (K_h)	feet per day	22	22	2.2
Vertical hydraulic conductivity (K_v)	feet per day	22	22	2.2
Specific yield storage coefficient (S_y)	dimensionless	0.01	0.01	0.01
Storage coefficient (S)	dimensionless	0.01	0.01	0.01
Porosity	dimensionless	0.01	0.01	0.01
Aquifer Transport Parameters				
K_d	cubic feet per pound	0	0	0
Aquifer bulk density	pounds per cubic foot	157	157	157
Dispersivity	feet	0	0	0

Recharge Amounts

Area/Feature	Recharge Rate (feet per day)
Areal recharge	0.0002
Disposal cell	0.0002
Evapotranspiration areas	0.0002

Figure 3. Summary of Parameters used in NRC Steady-State Model

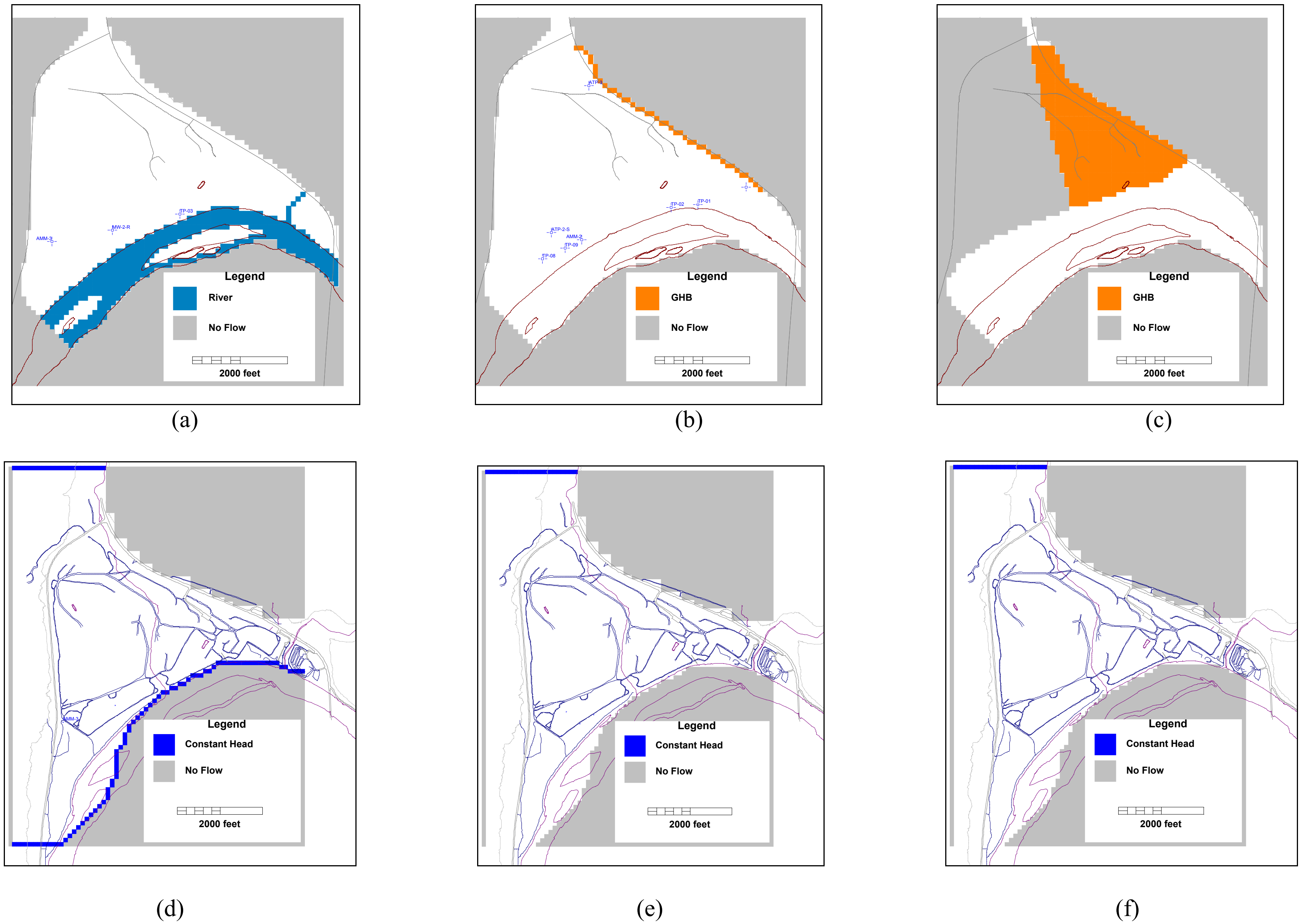


Figure 4. Boundary Conditions for SMI Model (a) Layer 1, (b) Layer 2, (c) Layer 3, and NRC Model (d) Layer 1, (e) Layer 2, (f) Layer 3

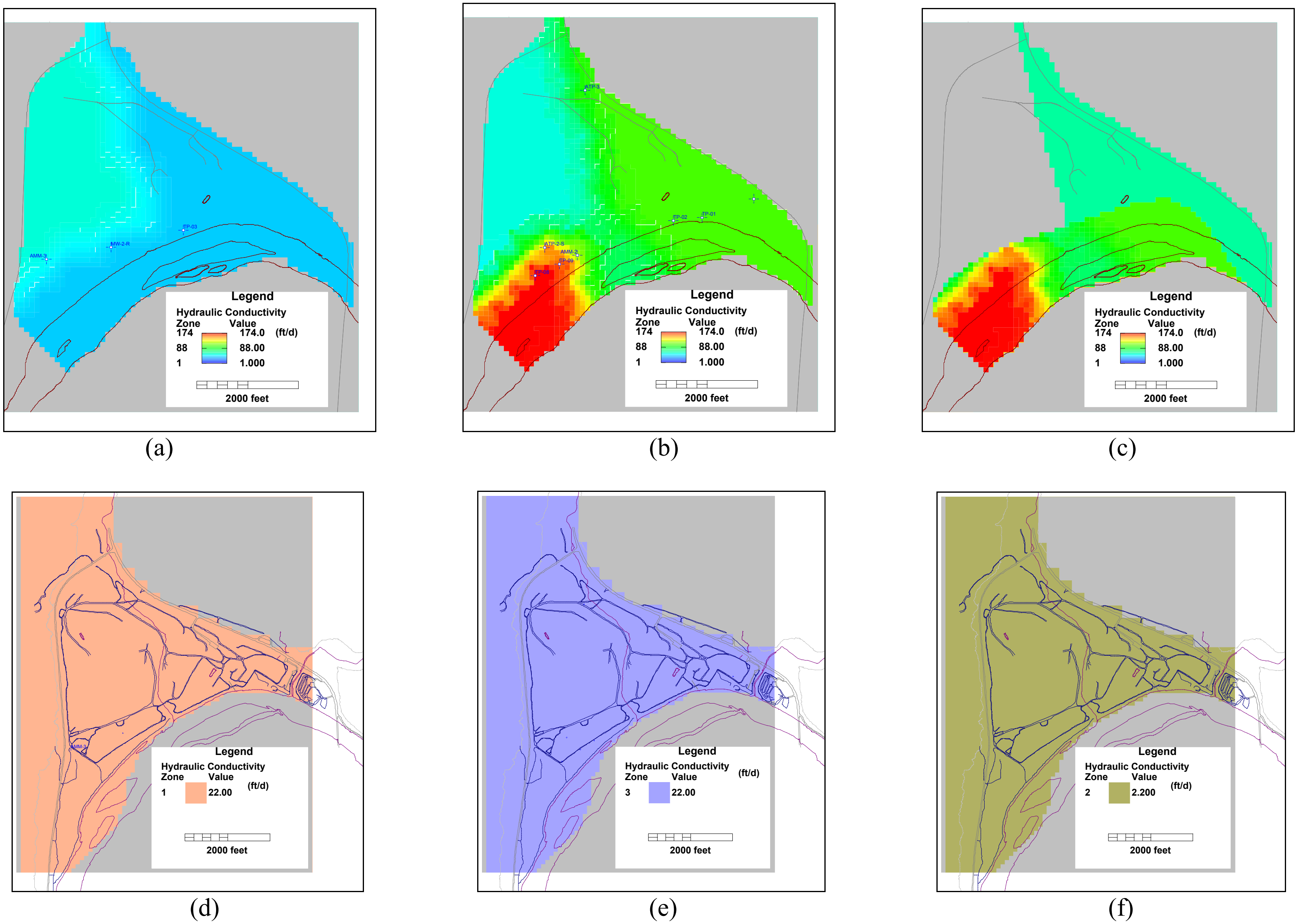
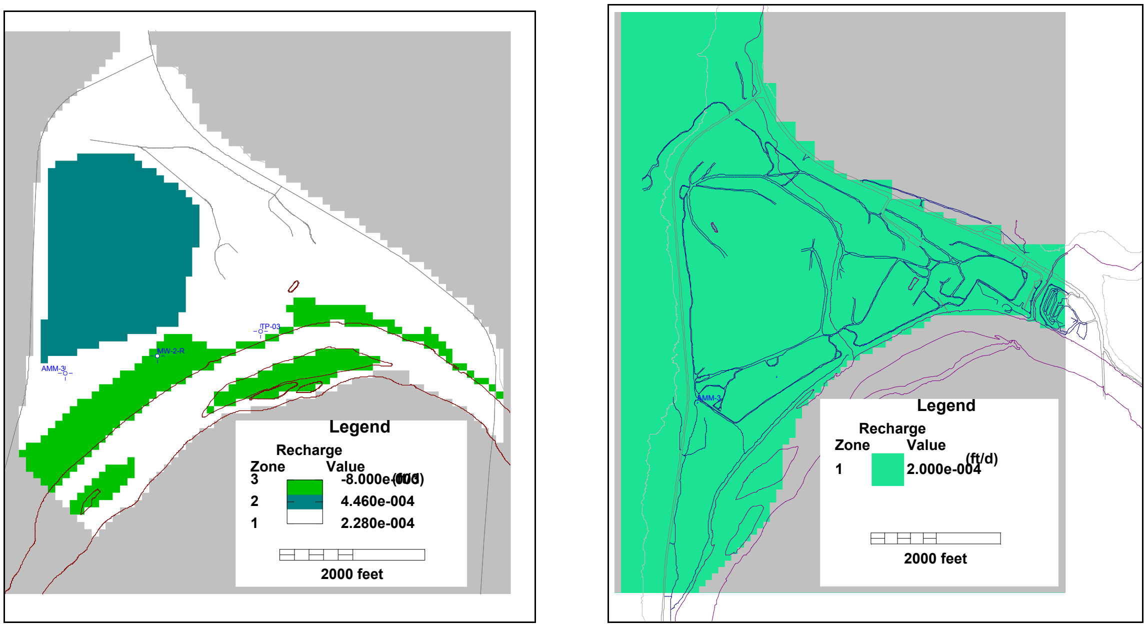
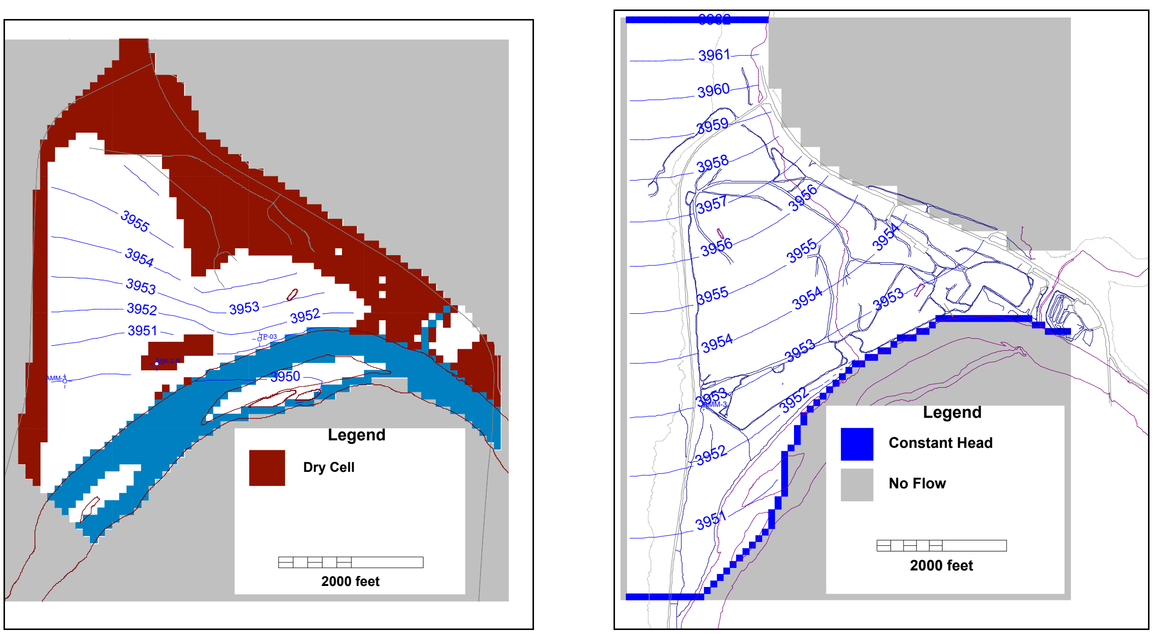


Figure 5. Hydraulic Conductivity for SMI Steady-State Model (a) Layer 1, (b) Layer 2, (c) Layer 3, and NRC Steady-State Model (d) Layer 1, (e) Layer 2, (f) Layer 3



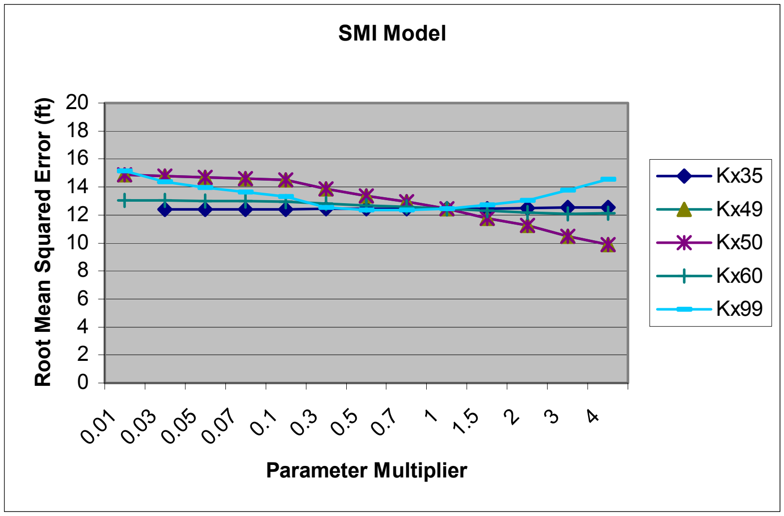
(a) (b)

Figure 6 Recharge Values for (a) SMI Steady-State Model and (b) NRC Steady-State Model

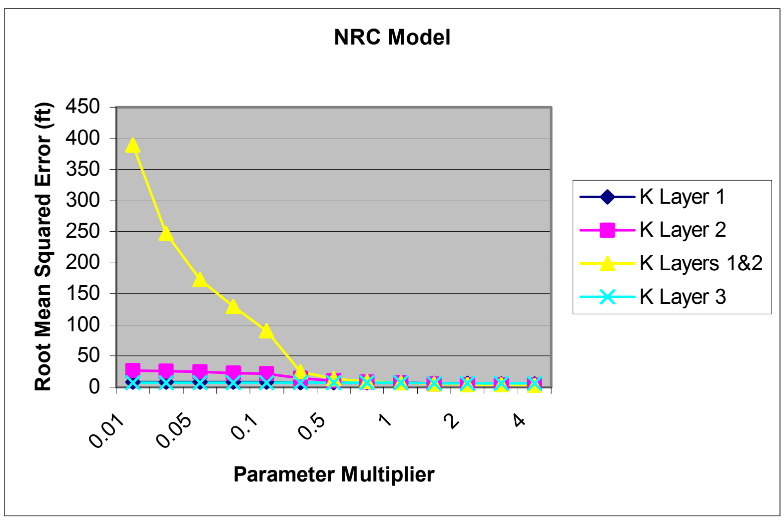


(a) (b)

Figure 7. Simulated Groundwater Contours in Layer 1 of (a) SMI Steady-State Model, and (b) NRC Steady-State Model

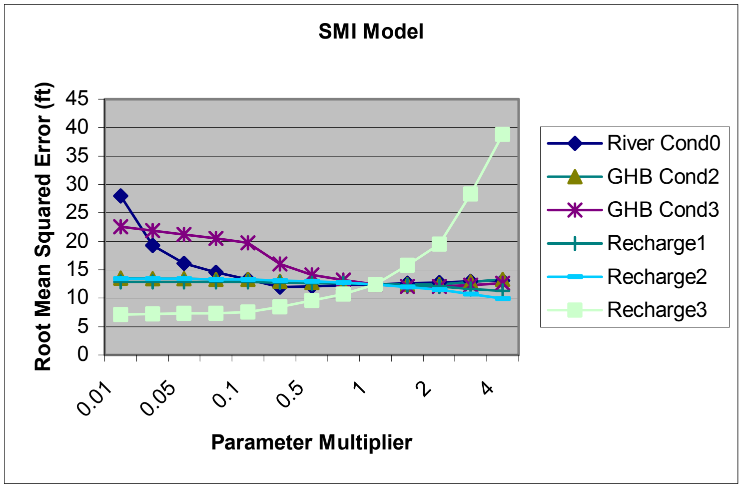


(a)

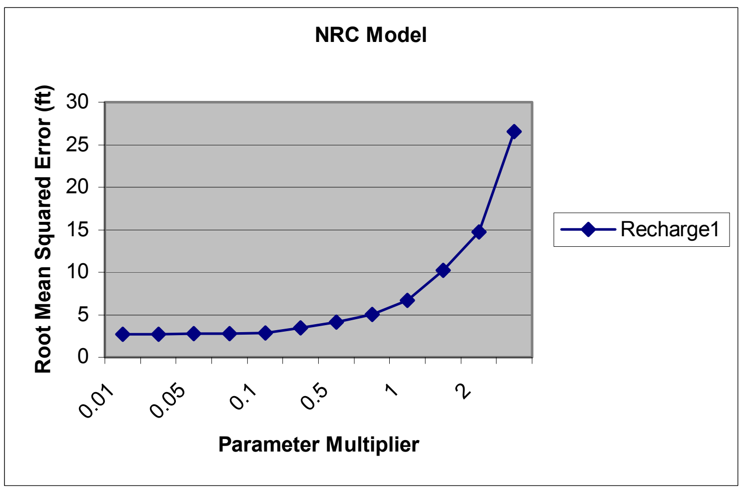


(b)

Figure 8. Sensitivity Analysis of Hydraulic Conductivity Parameter for (a) SMI Model and (b) NRC Model



(a)



(b)

Figure 9. Sensitivity Analysis of (a) Boundary Conditions and Recharge for SMI Model and (b) Recharge for NRC Model

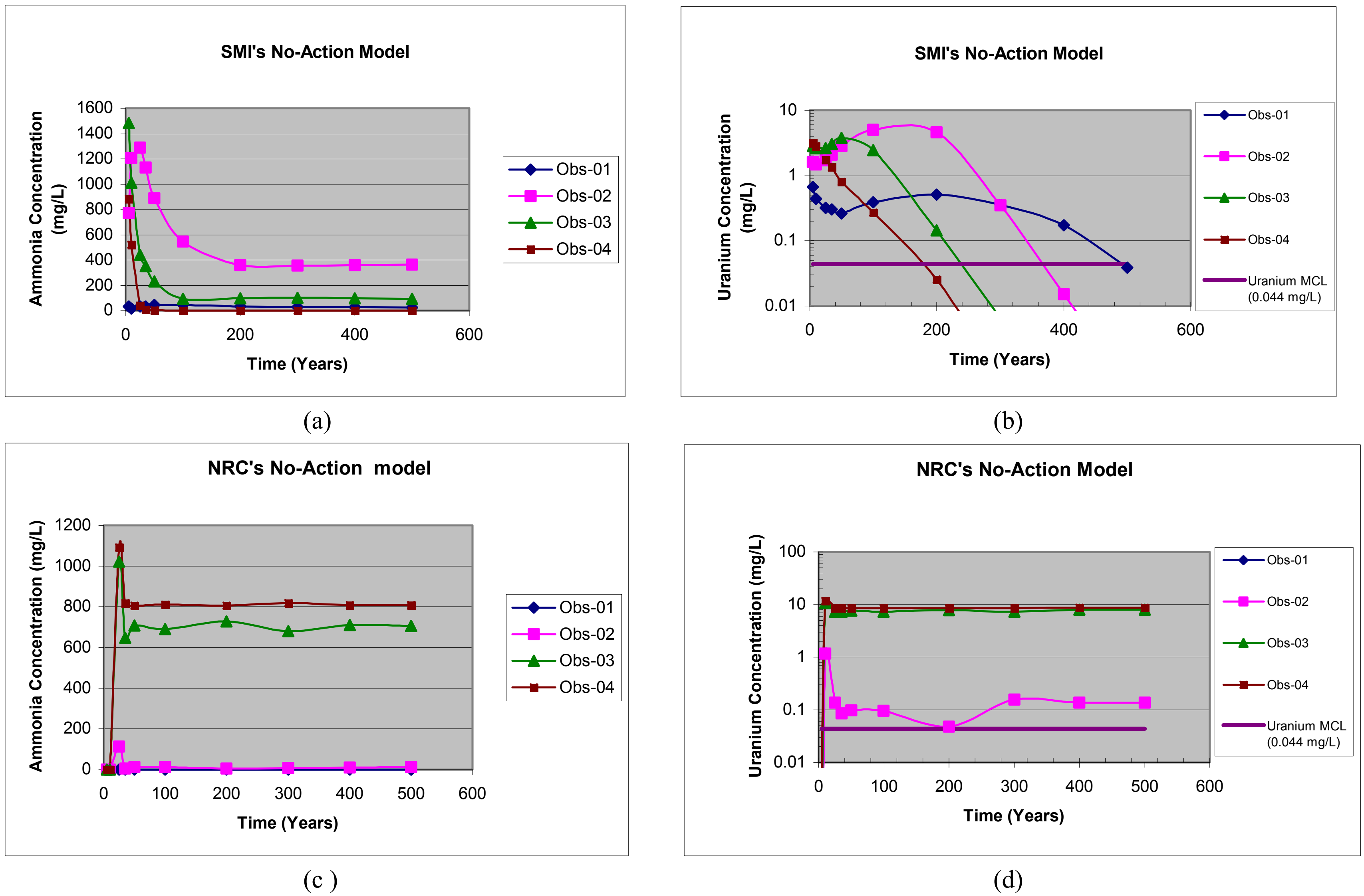
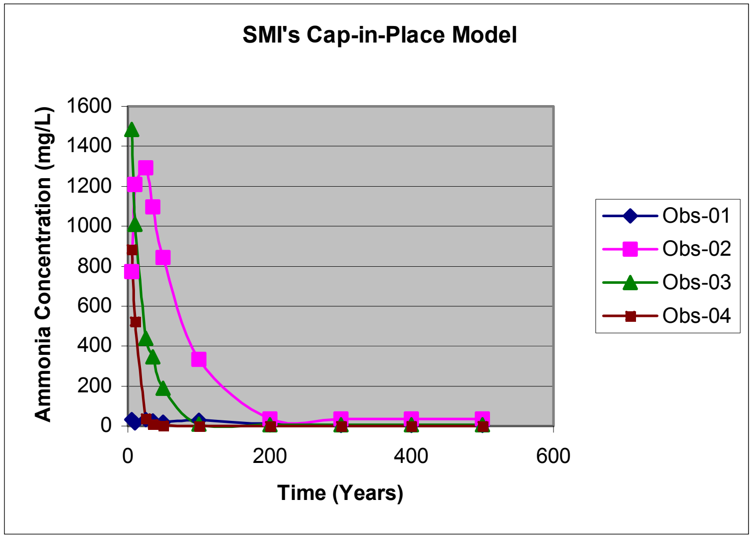
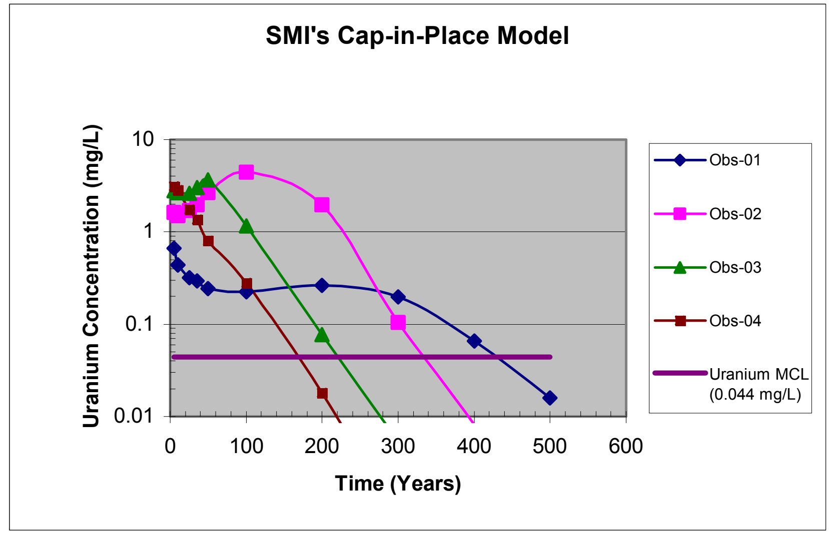


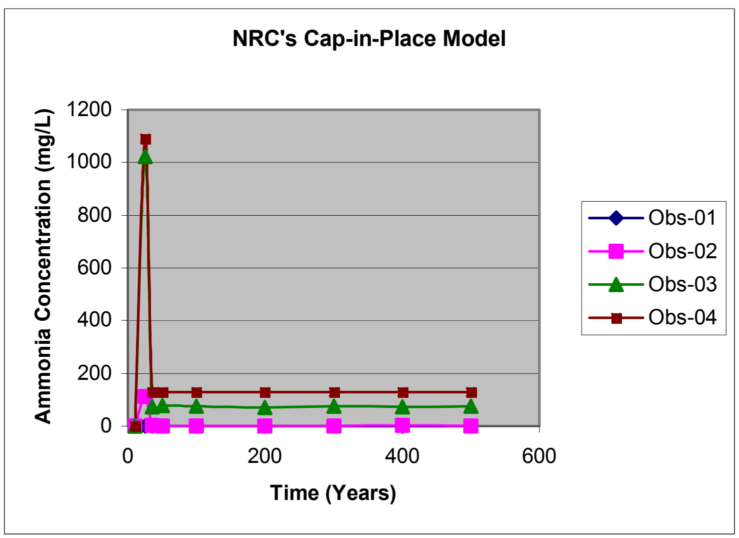
Figure 10. Comparison of Model-Predicted Concentrations of (a) Ammonia and (b) Uranium Computed with SMI No Action Model Versus (c) Ammonia and (d) Uranium Concentration Computed with NRC No Action Model



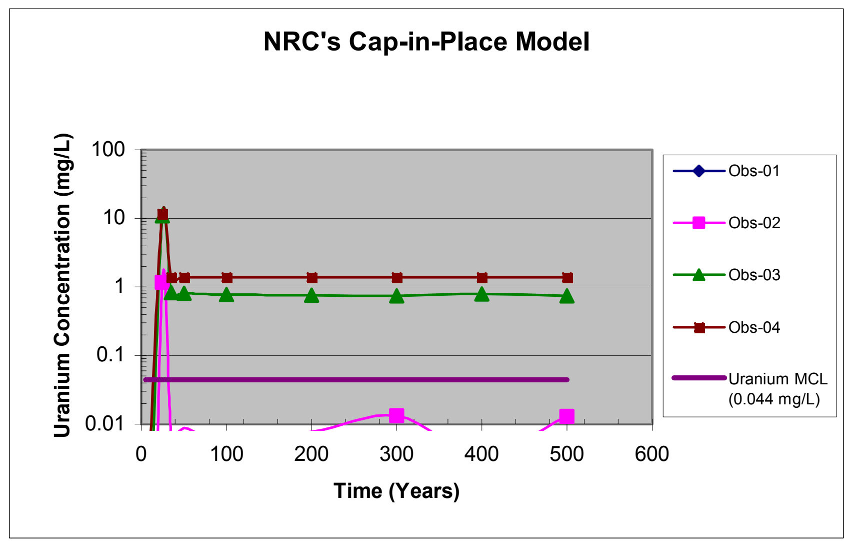
(a)



(b)

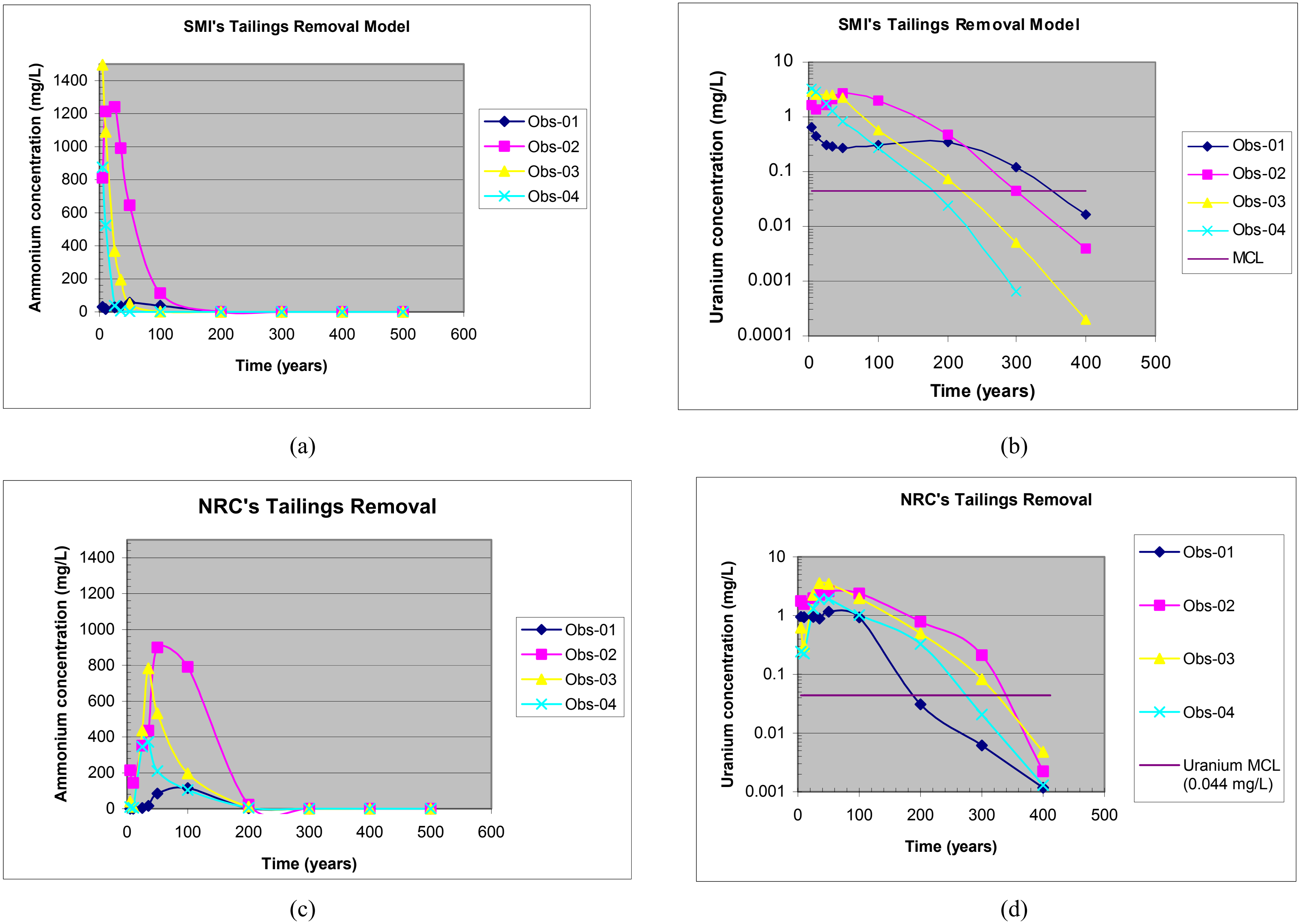


(c)



(d)

Figure 11. Comparison of Model-Predicted Concentrations of (a) Ammonia and (b) Uranium Computed with SMI Cap-in-Place Model Versus (c) Ammonia and (d) Uranium Concentration Computed With NRC Cap-in-Place Model



(a) (b) (c) (d)

Figure 12. Comparison of Model-Predicted Concentrations of (a) Ammonia and (b) Uranium Computed with SMI Source-Removal Model Versus (c) Ammonia and (d) Uranium Concentration Computed with NRC Source-Removal Model